



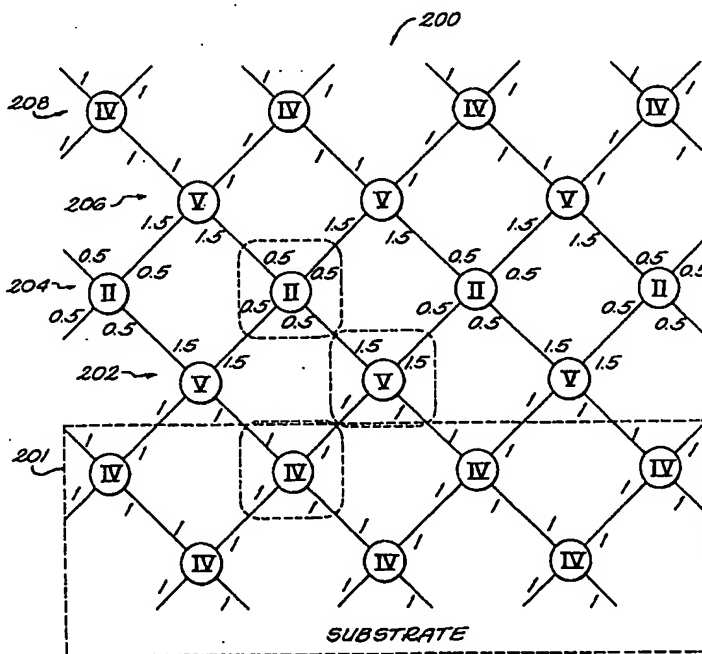
INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification ⁶ : H01L 3/00		A2	(11) International Publication Number: WO 99/63580
			(43) International Publication Date: 9 December 1999 (09.12.99)
(21) International Application Number: PCT/US99/11525 (22) International Filing Date: 25 May 1999 (25.05.99) (30) Priority Data: 09/087,166 29 May 1998 (29.05.98) US (71) Applicant: MASSACHUSETTS INSTITUTE OF TECHNOLOGY [US/US]; 77 Massachusetts Avenue, Cambridge, MA 02139 (US). (71)(72) Applicants and Inventors: WANG, Tairan [CN/US]; Room 418A, 305 Memorial Drive, Cambridge, MA 02139 (US). MOLL, Nikokaj [DE/US]; Wittelsbacherstrasse 10, D-10707 Berlin (DE). CHO, Kyeongjae [KR/US]; 1247 Lakeside Drive, #3033, Sunnyvale, CA 94086 (US). JOANNOPOULOS, John, D. [US/US]; 64 Douglas Road, Belmont, MA 02178 (US). (74) Agents: CONNORS, Matthew, E. et al.; Samuels, Gauthier & Stevens, Suite 3300, 225 Franklin Street, Boston, MA 02110 (US).		(81) Designated States: CA, JP, European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE). Published Without international search report and to be republished upon receipt of that report.	

(54) Title: COMPOUND SEMICONDUCTOR STRUCTURE WITH LATTICE AND POLARITY MATCHED HETEROEPITAXIAL LAYERS

(57) Abstract

A compound tetrahedrally coordinated semiconductor structure, whose chemical formula is generally of the form $II_nIII_mIV_lV_pVI_q$, where n, m, l, p, q represent the relative abundance of each element associated with a particular group of the periodic table. The flexibility of the chemical formula may be used to adjust the lattice constant and polarity to eliminate mismatches from substrates. Other properties, such as those of band gaps, can also be tuned. The design is amenable to layer-by-layer heteroepitaxial growth. In exemplary embodiments, a structure is provided that matches lattice constant and polarity with Si(100) surface, while having a direct band gap of $1.59\mu\text{m}$.



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COMPOUND SEMICONDUCTOR STRUCTURE WITH LATTICE AND POLARITY MATCHED HETEROEPITAXIAL LAYERS

BACKGROUND OF THE INVENTION

The invention relates to compound semiconductor structures provided with lattice and polarity matched heteroepitaxial layers.

There has been a major international effort on the heteroepitaxial growth of compound tetrahedrally coordinated semiconductors on Si substrates by MBE, MOCVD, etc.; on the fabrication of devices and circuits in these layers; and on the monolithic integration of such components with Si circuits fabricated on the same wafer. This effort is based on the significant potential that epitaxial growth of dissimilar semiconductor structures holds for technological applications. Nevertheless, relatively little theoretical work has been performed to understand the fundamental interactions and global issues governing the initial stages of growth and the structure of the first few mono-layers in these systems.

Of specific interest, for example, are the prototypical optically active systems GaAs on Si(100) and GaN on SiC/Si. At present, optoelectronics involves growth of structures like GaAs (an optical material because of its direct band-gap) on substrates of Si (an electronic material with an indirect band-gap). For the future, GaN is of particular interest for optoelectronics applications in the blue and near UV because of its direct wide band gaps. Unfortunately, the large lattice constant mismatches between the substrates and the epitaxial layers cause many defects to be created and propagate from the interface, as can be seen in Table 1 provided hereinafter. Moreover, this is exacerbated by the interface charge mismatch caused by polarity differences between GaAs and Si.

Table 1 illustrates the typical structures used in the electronics industry and their experimental lattice constant mismatches relative to Si $\Delta a/a_{Si}$. Most of the structures have a large lattice constant mismatch with Si. For those with a small lattice constant mismatch, there is still the problem of polarity mismatch.

Table 1.

Compound	$\Delta a/a_{Si}\{\%\}$	Polar
Si	0	no

Ge	+4.16	no
CuCl	-0.46	yes
ZnS	-0.41	yes
GaP	+0.37	yes
AlAs	+3.48	yes
GaAs	+4.11	yes
ZnSe	+4.36	yes
InP	+8.06	yes
InAs	+11.14	yes

Therefore, there is a need for a semiconductor structure with epitaxial layers that are polarity and lattice matched, and which exhibit tunable properties to obtain, for example, a direct band gap.

5

SUMMARY OF THE INVENTION

The invention provides a semiconductor structure specifically designed to consist of four to six types of atoms which on the average behave like Ga or As, by a systematic exploration of the geometric, electronic and optical properties of a new class of compound
 10 semiconductors. The flexibility in the choice of ordering and sizes of atoms is used to (1) match the polarity of the substrate surface, (2) eliminate the lattice mismatch and (3) tune other properties, such as obtaining a direct band-gap.

In cases where two tetrahedrally coordinated compounds can not grow directly on top of each other because of large lattice mismatches and/or polarity mismatches, a set of
 15 these new structures of gradually changing lattice constants can serve as buffer layers to bridge between the two target structures.

Some of the major problems facing heteroepitaxial growth of compound tetrahedrally coordinated semiconductors on various substrates are lattice constant mismatch and polarity mismatch. The invention provides a new type of compound
 20 tetrahedrally coordinated semiconductor, whose chemical formula is generally of the form $\text{II}_n\text{III}_m\text{IV}_l\text{V}_p\text{VI}_q$, where n, m, l, p, q represent the relative abundance of each element associated with a particular group of the periodic table. The flexibility of the chemical formula may be used to adjust the lattice constant and polarity to eliminate mismatches

from substrates. Other properties, such as those of band gaps, can also be tuned. The design is amenable to layer-by-layer heteroepitaxial growth. In exemplary embodiments, a structure is provided that matches lattice constant and polarity with a Si(100) surface, while having a direct band gap of 1.59 μ m.

5 **BRIEF DESCRIPTION OF THE DRAWINGS**

FIG. 1 is a schematic diagram of III-V structures grown on top of a group IV substrate 100.

FIG. 2 is a schematic diagram of a semiconductor structure in accordance with the invention;

10 FIG. 3 is a schematic diagram of the epitaxial layering of elements in accordance with the invention compared to that with III-V structures;

FIG. 4 is a depiction of Type I and Type II structures in accordance with the invention;

15 FIGs. 5 and 6 are tables of the estimated radii for Type I and Type II structures, respectively;

FIG. 7 is a plot of the lattice constants of Type I structures;

FIG. 8 is a plot of the lattice constants Type II structures;

FIG. 9 is a plot of the band structure of ZnSiAs₂ as calculated by LDA;

FIG. 10 is a plot of the band structure of ZnSiP₂ as calculated by LDA;

20 FIG. 11 is a plot of the ZnSi(P_xAs_{1-x})₂ lattice constant as a function of x, calculated with a local density functional method (LDA);

FIG. 12 is a plot of the ZnSi(P_xAs_{1-x})₂ size of band gap as a function of x, calculated with a quasi-particle *ab-initio* method;

25 FIG. 13 is a plot of the ZnSi(P_xAs_{1-x})₂ margin of directness of band gap as a function of x; and

FIG. 14 is a schematic diagram of a semiconductor crystal structure ZnSiP_{1/2}As_{3/2} in accordance with the invention.

DETAILED DESCRIPTION OF THE ILLUSTRATED EMBODIMENTS

30 The invention involves an epitaxial layer ordering scheme that ensures polarity matching between the epitaxial layers and any substrates. To better understand this ordering scheme, details related to a typical III-V structure on a tetrahedrally coordinated

homopolar substrate, such as Si(100), will be presented. Group IV atoms have 4 valence electrons, and contribute 1 electron to each bond in forming tetrahedral structures. Group V atoms have 5 valence electrons, and contribute 1.25 electrons to each bond in forming tetrahedral structures. Group III atoms have 3 valence electrons, and contribute 0.75 electrons to each bond in forming tetrahedral structures. A bond is complete when it consists of a total of 2 electrons.

At the (100) surface, the group IV atoms form two bonds with the first layer of group V atoms, contributing two electrons, one to each bond. The first layer group V atoms have to contribute only 1 electron to each of the two bonds with the group IV atoms in order to satisfy the 2-electron-per-bond counting rule. From there on, the bonds are formed between group V and group III atoms, with the former contributing 1.25 electrons to the bond and the latter 0.75 electrons. The net effect is that 0.5 electrons per group V atom from the first layer are redistributed all the way to the outer surface of the structure, thus creating a long range electric field that is undesirable.

FIG. 1 is a schematic diagram of III-V structures 100 grown on top of a group IV substrate 101. The atoms contribute electrons to each bond, as indicated by the numbers on the bonds. Group IV atoms contribute 1 electron to each bond, Group V (102) atoms contribute 1.25 electrons to each bond and Group III atoms (104) contribute 0.75 electrons to each bond. Each bond needs a total of 2 electrons. Electron counting shows that the first layer of Group V atoms at the interface ends up carrying positive charge because 0.5 electron per atom is redistributed to the surface to satisfy electron-counting rules.

FIG. 2 is a schematic diagram of a semiconductor structure 200 in accordance with the invention. The structure begins as before with a group IV substrate 201. A layer 202 of group V atoms is then deposited on top of it, followed by a layer 204 of group II atoms, then a layer 206 of group V atoms and finally a layer 208 of group IV atoms. This completes a cycle of elements in the growth direction, from group IV, to group V, to group II, to group V, and back to group IV. The procedure can then be repeated. It will be appreciated by those skilled in the art that the subsequent layers need to be from the same group, but do not necessarily need to be the same element. For example, the layer 202 of group V atoms can be Arsenic, while the subsequent layer 206 can also be Arsenic or some other group V element.

In terms of electron counting, the group IV atoms in the top layer of the substrate

contribute 1 electron to each bond with the first layer group V atoms. Every group V atom is surrounded by 2 group IV atoms and 2 group II atoms, while each group II atom is surrounded by 4 group V atoms. Group II atoms contribute 0.5 electron to each of the 4 bonds with group V atoms. Group V atoms contribute 1 electron to each of the 2 bonds
5 formed with group IV atoms, and 1.5 electrons to each of the 2 bonds formed with group II atoms. Electron counting shows that each bond has 2 electrons and there is no transport of electrons over long distances. Therefore, the electrostatic potential in the growth direction is localized and periodic. There is no long range field effect, in contrast to the case of growing III-V structure on top of group IV substrate. FIG. 3 is a schematic
10 diagram of the epitaxial layering of elements in accordance with the invention compared to that with III-V structures.

Accordingly, the charge mismatch problem of the interface is eliminated. Furthermore, there is much flexibility on the types of atoms one can use. In principle, each layer can be of a different element, as long as it belongs to the correct group. This
15 provides the designer with many choices in adjusting for other physical properties. The new compound semiconductor structure can be written in a short-hand chemical formula $(\text{II-IV})_{1/2}\text{V}$, while it is understood that there may be more than one component to any of the three groups. For example, given group II atoms Zn, Cd, group IV atoms Si, Ge, and group V atoms P, As, one could form the compound ... Si P Zn As Ge As Cd As Si.
20 This particular structure will be denoted as Type I.

To achieve the same effect, a different combination can also be utilized. The structure can start with the deposition with a layer of group III element, followed by group VI, group III, and then back to group IV. Written as a chemical formula, this is $\text{III}(\text{IV-VI})_{1/2}$, which will be referred to as Type II. FIG. 4 is a depiction of Type I and Type II
25 structures. Type I structures are composed of group II, IV, V elements. One example is ZnGeAs_2 . Type II structures are composed of III, IV, VI elements. One example is Ga_2SiS .

In another exemplary embodiment of the invention, the deposition begins with a layer of group II/VI atoms, followed by a layer of group VI/II atoms, followed by group
30 IV, group VI/II, group II/VI, and then back to group IV. Written as a chemical formula, this is $(\text{II})_{1/2}\text{IV}(\text{VI})_{1/2}$, which will be defined as a Type III structure.

All three Types solve the polarity mismatch problem. It will be appreciated by

those skilled in the art that combinations of them may also be considered. For example:
substrate -- Type I / Type II / Type III -- Type I / Type II / Type III --...

Moreover, the procedure is not limited to homopolar group IV substrates. When
some heteropolar substrate is used, such as GaAs, one can simply start the procedure from
5 the appropriate layer. For example, the layering order can be

III V III V IV V II V IV

or

III V III V II V IV V II V IV

10 These procedures leave the structure designers with many choices. Different types
of atoms and different layering orders can all play a role in influencing the lattice constant
and other properties of the resulting structure. Since some structures will certainly be
easier to fabricate than others, it is also important to accumulate a large pool of candidate
structures for various lattice constants and other properties.

15 The description of the design of a particular structure where the objective is to
match lattice constant and polarity with Si(100) surface and to have a direct band gap in
the 1 eV range will now be provided. Since the number of possible choices of atom types
and Type I/II layered sequences are enormous, the simple structures were searched first,
and the complexity involved was gradually increased.

20 As a start, data was used on the tetrahedral covalent radii of various elements from
Kittel, *Introduction to Solid State Physics*, John Wiley & Sons, 7th ed., p. 78 (1996), and
Shay, *Ternary chalcopyrite semiconductors: growth, electronic properties, and
applications*, Pergamon Press, Vol. 7, p. 9 (1975), both of which are incorporated herein
by reference, to get the approximate lattice constants of various structures. FIGs. 5 and
6 are tables of the estimated radii for Type I and Type II structures, respectively. This
25 estimating procedure only provides a rough estimate of the real lattice constants and can
have an error as large as 4%. To get the true lattice constants of the structures of interest,
ab-initio total energy pseudopotential calculations are utilized.

FIGs. 7 and 8 are plots of the lattice constants of Type I and Type II structures,
respectively. The estimated lattice constants are provided on the left side of the plots. On
30 the right side of the plots are the results based on *ab-initio* calculations. Several
compounds containing oxygen do not have tetrahedral bonding as their stable
configurations. They are indicated by x.

The local density approximation (LDA) of the density functional theory is used to minimize the electronic energy using the preconditioned conjugate gradients scheme. The LDA calculations are performed with the Perdew-Zunger parameterized exchange-correlation energy, and the Kleinman-Bylander separable form of optimized pseudopotentials.

The total energy is a function of the lattice vectors as well as the relative ion positions. The ions are relaxed according to the Hellman-Feynman forces for each given set of lattice vectors. The lattice constant is then located by finding the minimum of the total energy in the lattice vector space.

The cutoff energy used in the calculations is $E_c = 12$ Ry, except for structures involving first row elements, where $E_c = 30$ Ry is used. Experiences show that the lattice constants, calculated using the procedure described, are within 1% of the true values. Once promising structures with the correct lattice constants are found, a quasi-particle GW scheme is used to get accurate information on band gaps.

Different configurations were systematically attempted, in the order of their likelihood for matching Si lattice constant. Among all the structures investigated, three candidates were identified that may match lattice constant with Si – ZnSiAs_2 , In_2CSe , and In_2CS . Unfortunately, all have indirect band gaps. However, the structure ZnSiP_2 , despite a large lattice constant mismatch (3%), does possess a direct band gap. The band structures of ZnSiAs_2 and ZnSiP_2 are shown in FIG. 9 is a plot of the and 10.

FIG. 9 is a plot of the band structure of ZnSiAs_2 as calculated by LDA. FIG. 10 is a plot of the band structure of ZnSiP_2 as calculated by LDA. GW calculation widens the gap but does not change the overall shape of the bands or the directness of the gap.

The valence bands are shadowed. The valence band maximum is indicated by a filled dot and the conduction band minimum is indicated by an empty dot.

The epitaxial layering scheme allows for the use of different group V elements in different layers of one structure, so ZnSiAs_2 and ZnSiP_2 were mixed in searching for a combination that will provide both the correct lattice constant and the desired band gap.

This new type of semiconductor structure can be written as $\text{ZnSi}(\text{P}_x\text{As}_{1-x})_2$, where x indicates the relative percentage of Phosphorus used.

Several structures were studied with different x values, and thus the trend of lattice constant and band gap as x varies was established. FIG. 11 is a plot of the $\text{ZnSi}(\text{P}_x\text{As}_{1-x})_2$

lattice constant as a function of x , calculated with a local density functional method (LDA). From FIG. 11 is a plot of it is clear that a good lattice match can be found near $x = 0.25$. The results (FIGs. 12 and 13) show that the gap is indeed direct and is about 0.78 eV, corresponding to 1.59 μm infrared, which is very close to the 1.5 μm that
 5 optoelectronic industry uses. It will be appreciated by those of skill in the art that it is desirable to obtain gaps of approximately between 1.3 μm and 1.6 μm , which is in the range of those gaps utilized in the optoelectronics industry.

FIG. 12 is a plot of the $\text{ZnSi}(\text{P}_x\text{As}_{1-x})_2$ size of band gap as a function of x , calculated with a quasi-particle *ab-initio* method. FIG. 13 is a plot of the $\text{ZnSi}(\text{P}_x\text{As}_{1-x})_2$
 10 margin of directness of band gap as a function of x . The gap is direct when the margin is positive, and is measured by the difference between the lowest and the next lowest conduction band minimum. The gap is indirect when the margin is negative, and is measured by the difference between the lowest conduction band minimum and the lowest conduction band energy above the valence band maximum, and calculated with a quasi-
 15 particle *ab-initio* method. The chemical formula of this structure is $(\text{ZnSi})_{1/2}\text{P}_{0.25}\text{As}_{0.75}$.

FIG. 14 is a schematic diagram of a semiconductor crystal structure $\text{ZnSiP}_{1/2}\text{As}_{3/2}$ in accordance with the invention. The structure has all the desired properties for an optical structure growing on Si(100) surface. The specific layering order is
 ... P Zn As Si As Zn As Si ...

20 The sequence is then repeated. The lattice constant is only 0.08% smaller than that of Si, according to the *ab-initio* study.

Although the present invention has been shown and described with respect to several preferred embodiments thereof, various changes, omissions and additions to the form and detail thereof, may be made therein, without departing from the spirit and scope
 25 of the invention.

What is claimed is:

CLAIMS

- 1 1. A semiconductor structure comprising:
2 a substrate having an outer surface layer of a group IV element;
3 a first layer of a group V element provided on said outer surface layer;
4 a second layer of a group II element provided on said first layer;
5 a third layer of a group V element provided on said second layer; and
6 a fourth layer of a group IV element provided on said third layer.
- 1 2. The semiconductor structure of claim 1 further comprising subsequent layers
2 provided on said fourth layer.
- 1 3. The semiconductor structure of claim 2, wherein said subsequent layers
2 comprise at least one device.
- 1 4. The semiconductor structure of claim 1 further comprising a subsequent
2 sequence of said first, second, third and fourth layers provided on said fourth layer.
- 1 5. The semiconductor structure of claim 1, wherein desired lattice constants are
2 obtained in accordance with the selection of the group elements for each layer.
- 1 6. The semiconductor structure of claim 1, wherein the group elements for each
2 layer are selected to achieve lattice matching to said substrate.
- 1 7. The semiconductor structure of claim 1, wherein the group elements of each
2 layer are selected to obtain a band gap.
- 1 8. The semiconductor structure of claim 1, wherein the group of elements of each
2 layer are selected to obtain a direct band gap.
- 1 9. The semiconductor structure of claim 1, wherein the group of elements of each
2 layer are selected to obtain a band gap of approximately between 1.3 μ m and 1.6 μ m.

1 10. The semiconductor structure of claim 1, wherein said structure comprises the
2 formula $\text{ZnSiP}_{2x}\text{As}_{2(1-x)}$.

1 11. The semiconductor structure of claim 1, wherein said structure comprises the
2 formula $\text{ZnSiP}_{1/2}\text{As}_{3/2}$, where $x \approx 1/4$.

1 12. A semiconductor structure comprising:
2 a substrate having an outer surface layer of a group IV element;
3 a first layer of a group III element provided on said outer surface layer;
4 a second layer of a group VI element provided on said first layer;
5 a third layer of a group III element provided on said second layer; and
6 a fourth layer of a group IV element provided on said third layer.

1 13. The semiconductor structure of claim 12 further comprising subsequent layers
2 provided on said fourth layer.

1 14. The semiconductor structure of claim 13, wherein said subsequent layers
2 comprise at least one device.

1 15. The semiconductor structure of claim 12 further comprising a subsequent
2 sequence of said first, second, third and fourth layers provided on said fourth layer.

1 16. The semiconductor structure of claim 12, wherein desired lattice constants are
2 obtained in accordance with the selection of the group elements for each layer.

1 17. The semiconductor structure of claim 12, wherein the group elements for each
2 layer are selected to achieve lattice matching to said substrate.

1 18. The semiconductor structure of claim 12, wherein the group elements of each
2 layer are selected to obtain a band gap.

1 19. The semiconductor structure of claim 12, wherein the group of elements of

2 each layer is selected to obtain a direct band gap.

1 20. The semiconductor structure of claim 12, wherein the group of elements of
2 each layer are selected to obtain a band gap of approximately between 1.3 μ m and 1.6 μ m.

1 21. The semiconductor structure of claim 12, wherein said structure comprises the
2 formula $\text{InCS}_x\text{Se}_{(1-x)}$.

1 22. The semiconductor structure of claim 12, wherein said structure comprises the
2 formula $\text{InCS}_{2/3}\text{Se}_{1/3}$, where $x \approx 1/3$.

1 23. A semiconductor structure comprising:
2 a substrate having an outer surface layer of a group IV element;
3 a first layer of one of a group II or a group VI element provided on said outer
4 surface layer;
5 a second layer of the other of a group II or a group VI element provided on said
6 first layer; and
7 a third layer of a group IV element provided on said second layer.

1 24. The semiconductor structure of claim 23 further comprising:
2 a fourth layer provided on said third layer, said fourth layer being an element from
3 the same group as said second layer;
4 a fifth layer provided on said fourth layer, said fifth layer being an element from
5 the same group as said first layer; and
6 a sixth layer of a group IV element provided on said fifth layer.

1 25. The semiconductor structure of claim 23 further comprising:
2 a fourth layer provided on said third layer, said fourth layer being an element from
3 the same group as said first layer;
4 a fifth layer provided on said fourth layer, said fifth layer being an element from
5 the same group as said second layer; and
6 a sixth layer of a group IV element provided on said fifth layer.

1 26. The semiconductor structure of claim 23, wherein desired lattice constants are
2 obtained in accordance with the selection of the group elements for each layer.

1 27. The semiconductor structure of claim 23, wherein the group elements for each
2 layer are selected to achieve lattice matching to said substrate.

1 28. The semiconductor structure of claim 23, wherein the group elements of each
2 layer are selected to obtain a band gap.

1 29. The semiconductor structure of claim 23, wherein the group of elements of
2 each layer is selected to obtain a direct band gap.

1 30. A semiconductor structure comprising:
2 a substrate having an outer surface layer of a group IV element;
3 a first layer of an element, selected such that the absolute value of the difference
4 between the valence of the group IV element of the outer surface layer and the valence of
5 the element of said first layer is one, provided on said outer surface layer;
6 a second layer of an element, selected such that the absolute value of the difference
7 between the valence of the element of said second layer minus the valence of the element
8 of said first layer is three, provided on said first layer;
9 a third layer of an element, selected such that the absolute value of the difference
10 between the valence of the element in said third layer and the valence of the element in
11 the second layer is three, provided on said second layer; and
12 a fourth layer of a group IV element provided on said third layer.

1 31. A semiconductor structure comprising:
2 a substrate having a surface;
3 a plurality of epitaxial layers provided on said surface, said epitaxial layers being
4 selected in order to match polarity and eliminate lattice mismatch with said surface and
5 to obtain a direct band gap.

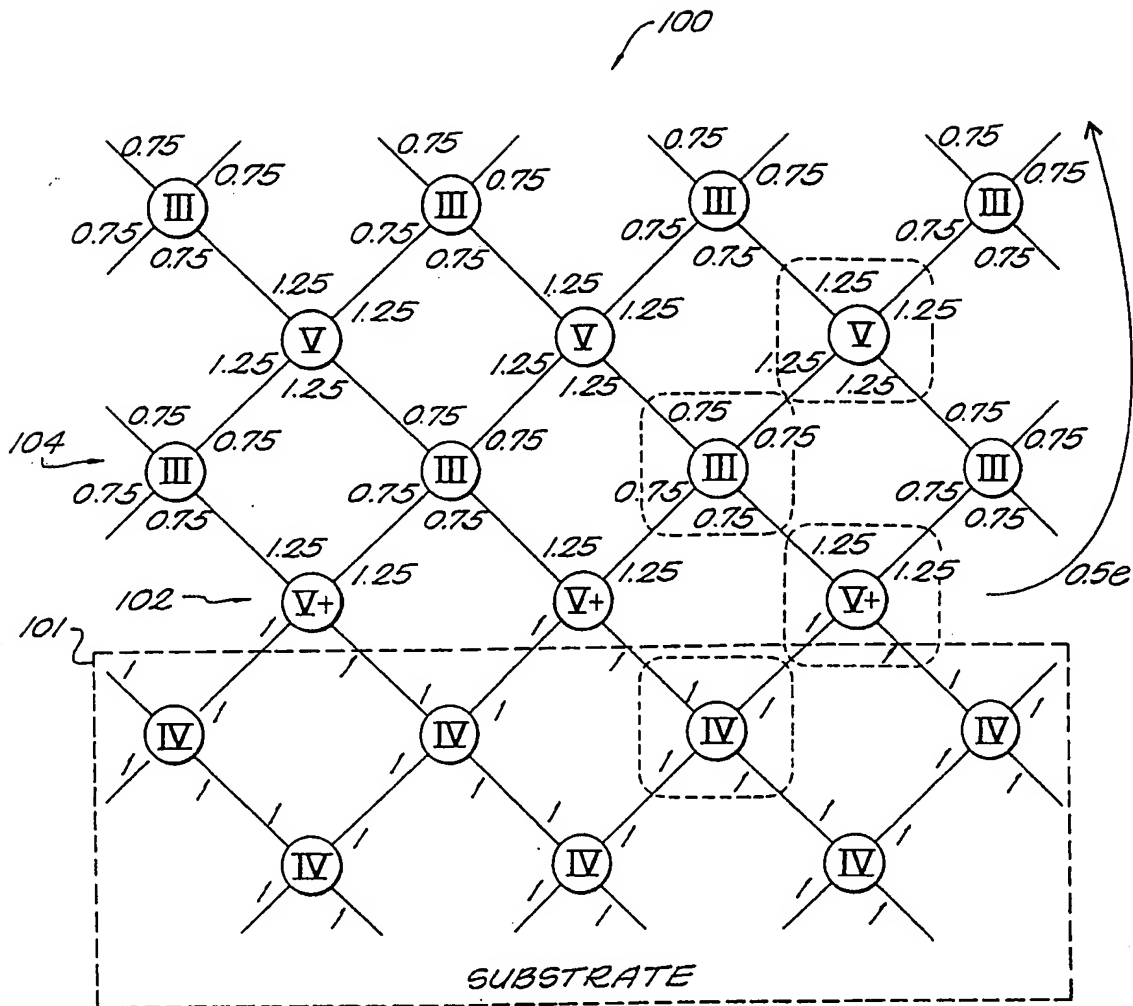
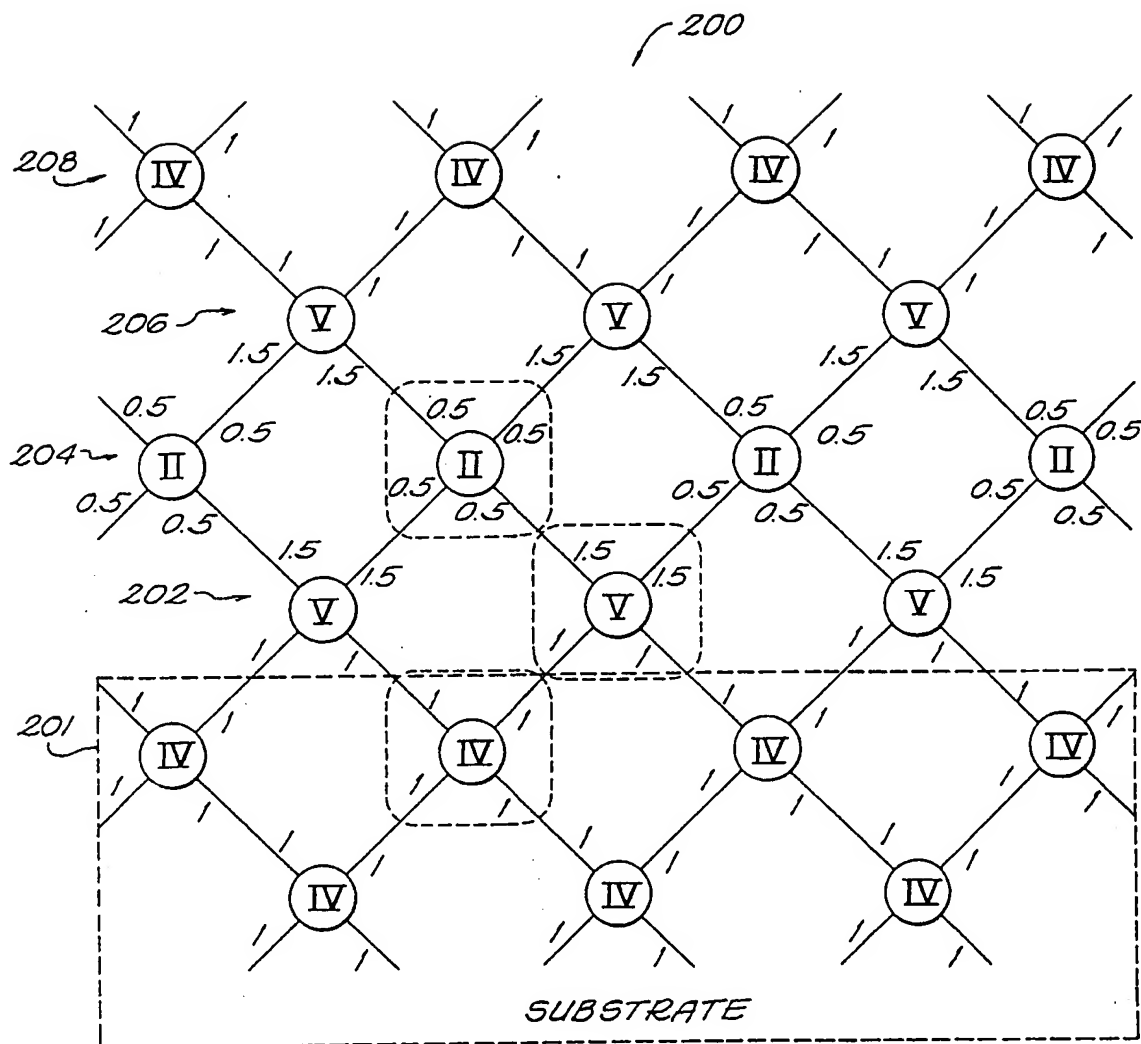
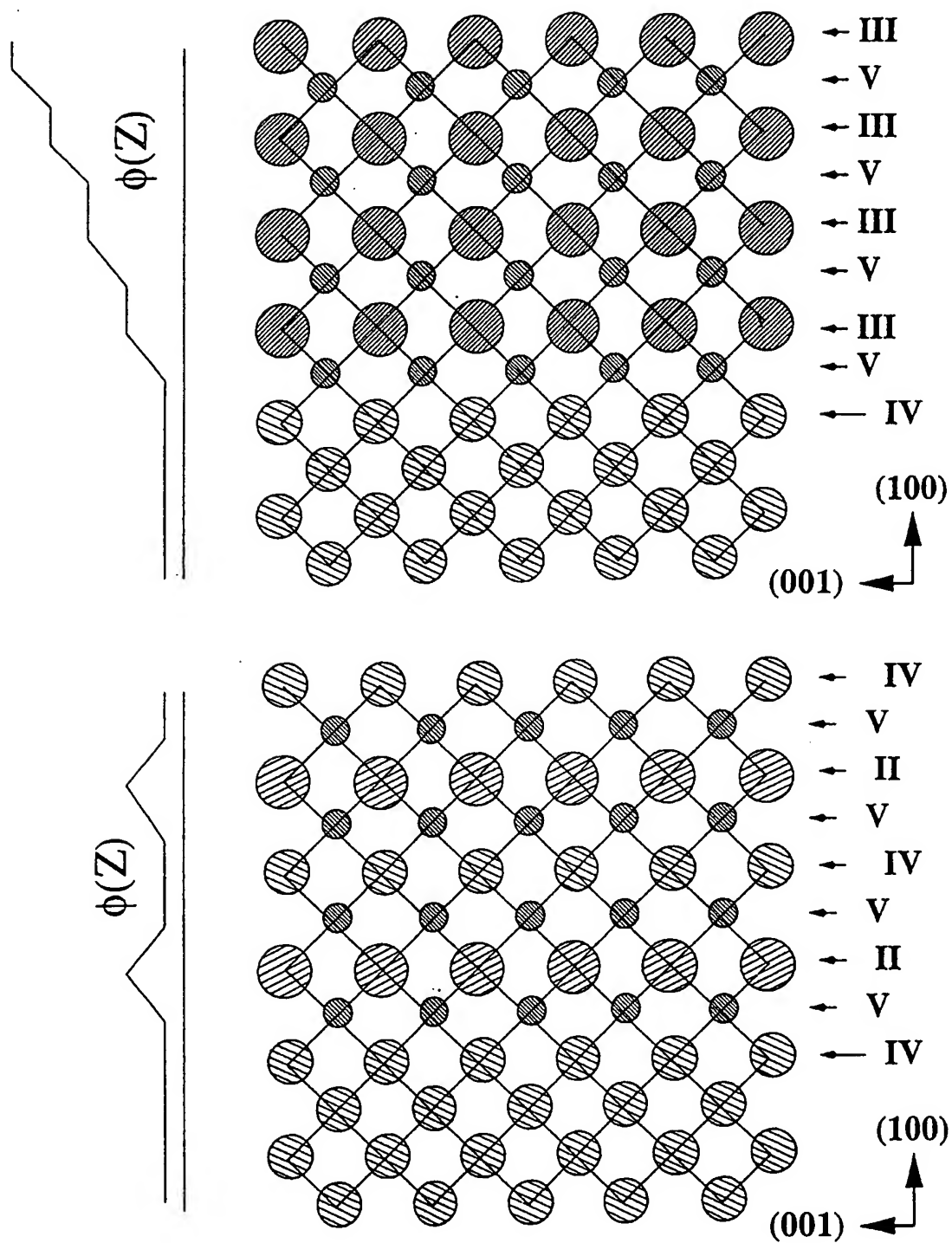


FIG. 1

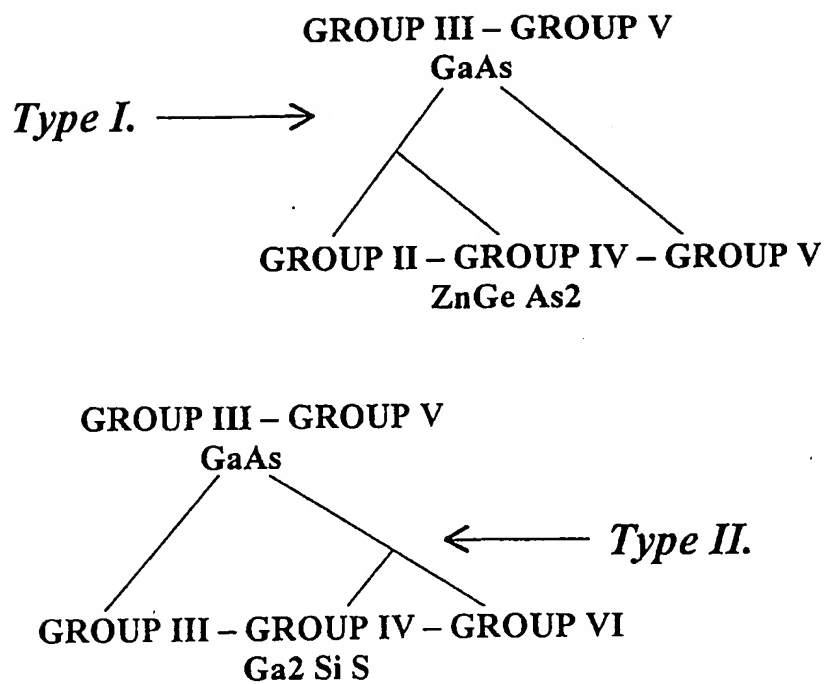
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**FIG. 2**

3/12

**FIG. 3**

4/12

**FIG. 4**

5/12

ESTIMATED RADII FOR TYPE I

Structure	$a[\text{\AA}]$	$\Delta a[\%]$
MgCP ₂	3.487854	-8.723598
CdSnN ₂	3.493383	-8.578903
CdCP ₂	3.531347	-7.585385
ZnCAS ₂	3.568605	-6.610363
BeSiP ₂	3.614845	-5.400270
MgCAS ₂	3.621783	-5.218700
BeGeP ₂	3.653218	-4.396053
CdCAS ₂	3.666256	-4.054861
BeCSb ₂	3.699748	-3.178363
BeSiAs ₂	3.745563	-1.979416
BeGeAs ₂	3.784020	-0.972981
BeSnP ₂	3.784231	-0.967472
ZnSiP ₂	3.817774	-0.089665
ZnGeP ₂	3.860629	1.031844
ZnCSb ₂	3.867224	1.204444
MgSiP ₂	3.885559	1.684262
BeSnAs ₂	3.915581	2.469927
MgCSb ₂	3.922169	2.642329
MgGeP ₂	3.929998	2.847222
CdSiP ₂	3.943594	3.203013
ZnSiAs ₂	3.948527	3.332127
CdCSb ₂	3.968522	3.855373
CdGeP ₂	3.989456	4.403230
ZnGeAs ₂	3.991314	4.451853
ZnSnP ₂	4.007650	4.879348
MgSiAs ₂	4.016499	5.110945
BeSiSb ₂	4.039659	5.717019
MgGeAs ₂	4.060816	6.270710
CdSiAs ₂	4.074772	6.635923
BeGeSb ₂	4.078287	6.727923
MgSnP ₂	4.082483	6.837719
CdGeAs ₂	4.120462	7.831632
ZnSnAs ₂	4.138332	8.299271
CdSnP ₂	4.146773	8.520179

FIG. 5

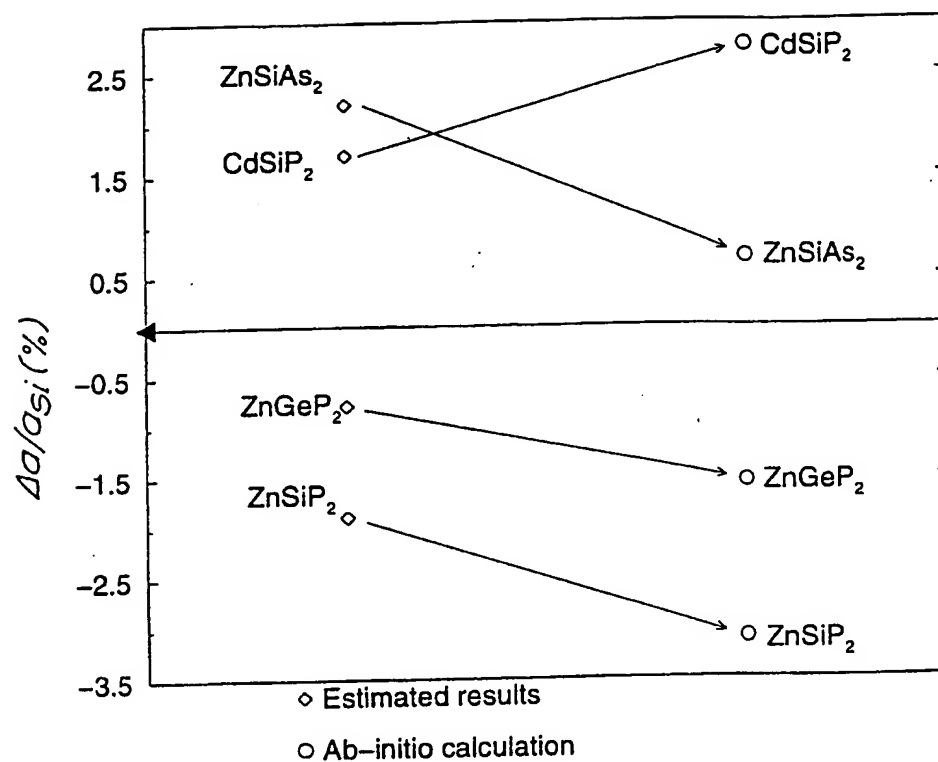
6/12

ESTIMATED RADII FOR TYPE II

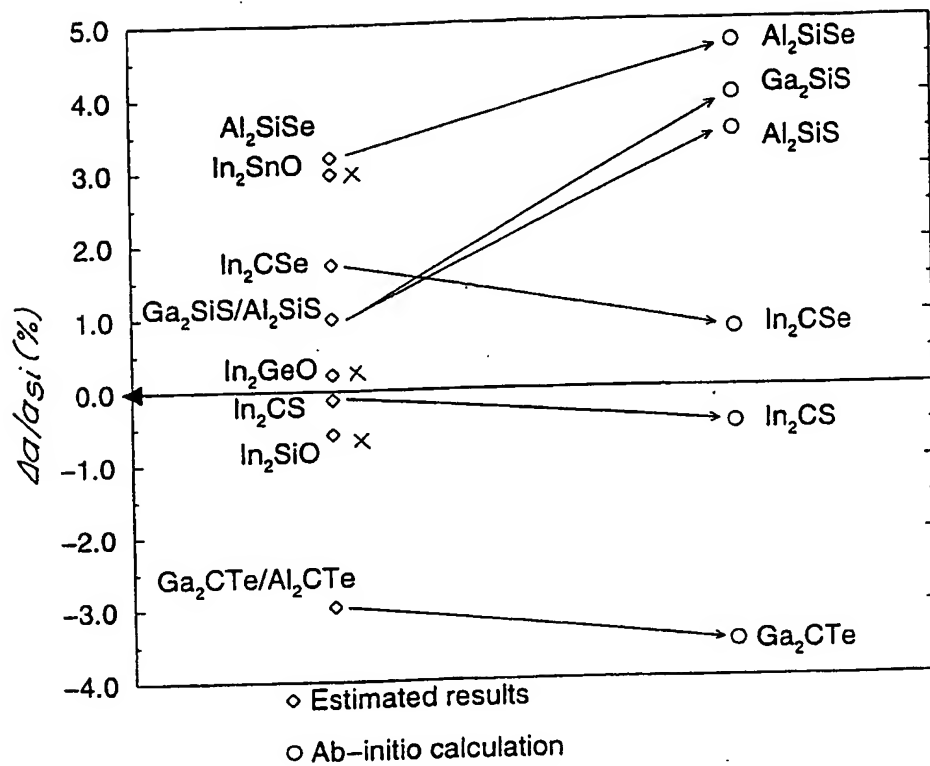
Structure	$a[\text{\AA}]$	$\Delta a[\%]$
B ₂ SiTe	3.465769	-9.301558
B ₂ SnSe	3.497932	-8.459863
Al ₂ SiO	3.500403	-8.395181
Ga ₂ SiO	3.500403	-8.395181
B ₂ GeTe	3.509033	-8.169348
In ₂ CO	3.516803	-7.966012
Al ₂ CS	3.521493	-7.843279
Ga ₂ CS	3.521493	-7.843279
Al ₂ GeO	3.530776	-7.600324
Ga ₂ GeO	3.530776	-7.600324
Al ₂ CSe	3.591208	-6.018845
Ga ₂ CSe	3.591208	-6.018845
Al ₂ SnO	3.631530	-4.963632
Ga ₂ SnO	3.631530	-4.963632
B ₂ SnTe	3.656737	-4.303963
Al ₂ CTe	3.707582	-2.973359
Ga ₂ CTe	3.707582	-2.973359
In ₂ SiO	3.798635	-0.590514
In ₂ CS	3.816528	-0.122272
In ₂ GeO	3.829916	0.228093
Al ₂ SiS	3.859104	0.991934
Ga ₂ SiS	3.859104	0.991934
In ₂ CSe	3.887180	1.726671
Al ₂ GeS	3.897292	1.991300
Ga ₂ GeS	3.897292	1.991300
In ₂ SnO	3.934890	2.975235
Al ₂ SiSe	3.943526	3.201254
Ga ₂ SiSe	3.943526	3.201254
Al ₂ GeSe	3.983431	4.245564
Ga ₂ GeSe	3.983431	4.245564
In ₂ CTe	4.006012	4.836492
Al ₂ SnS	4.028084	5.414113
Ga ₂ SnS	4.028084	5.414113
Al ₂ SiTe	4.086969	6.955130
Ga ₂ SiTe	4.086969	6.955130
Al ₂ SnSe	4.120462	7.831632
Ga ₂ SnSe	4.120462	7.831632
Al ₂ GeTe	4.129857	8.077485
Ga ₂ GeTe	4.129857	8.077485
In ₂ SiS	4.153250	8.689690
In ₂ GeS	4.191623	9.693903

FIG. 6

7/12

**FIG. 7**

8/12

**FIG. 8**

9/12

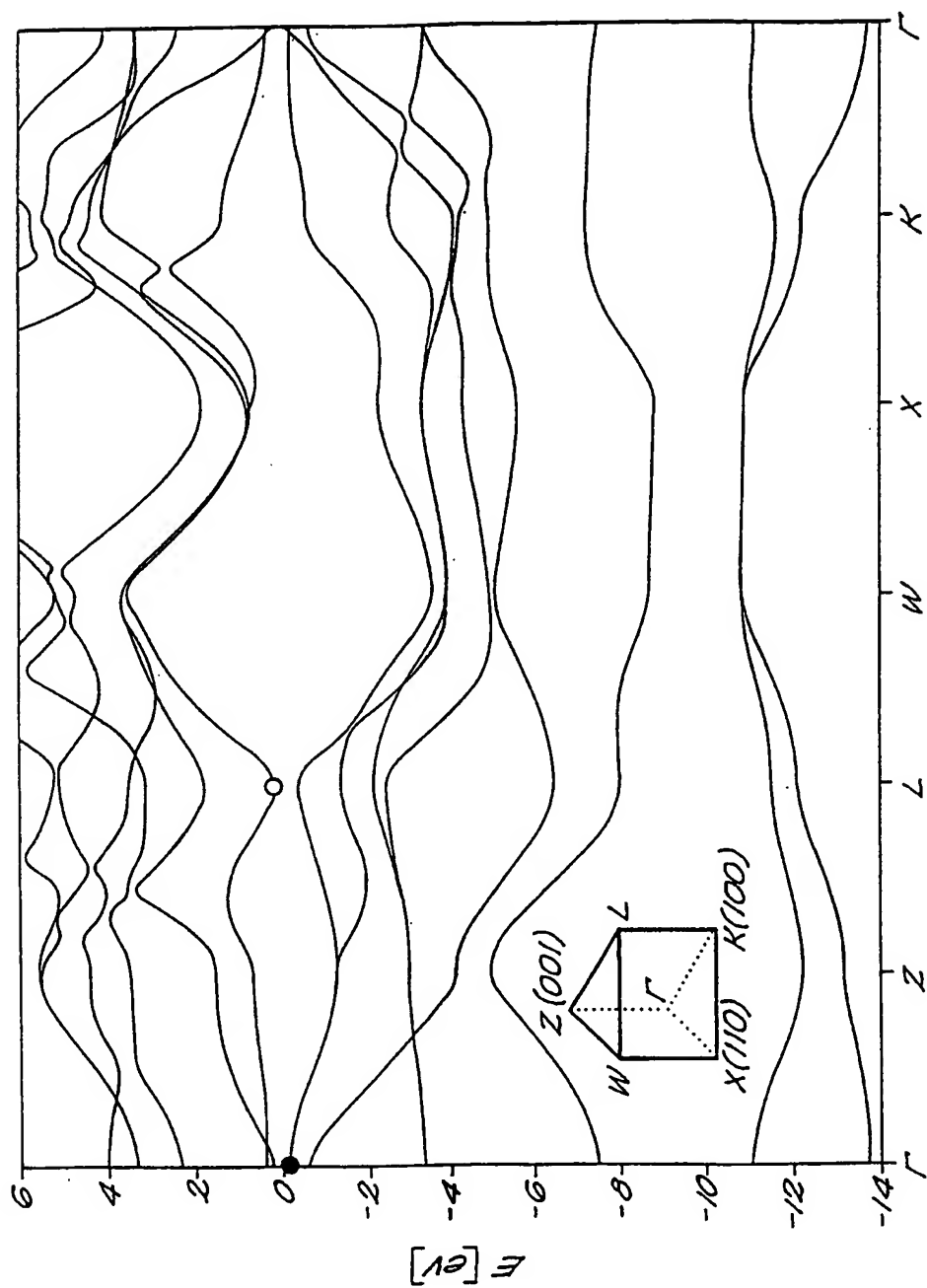
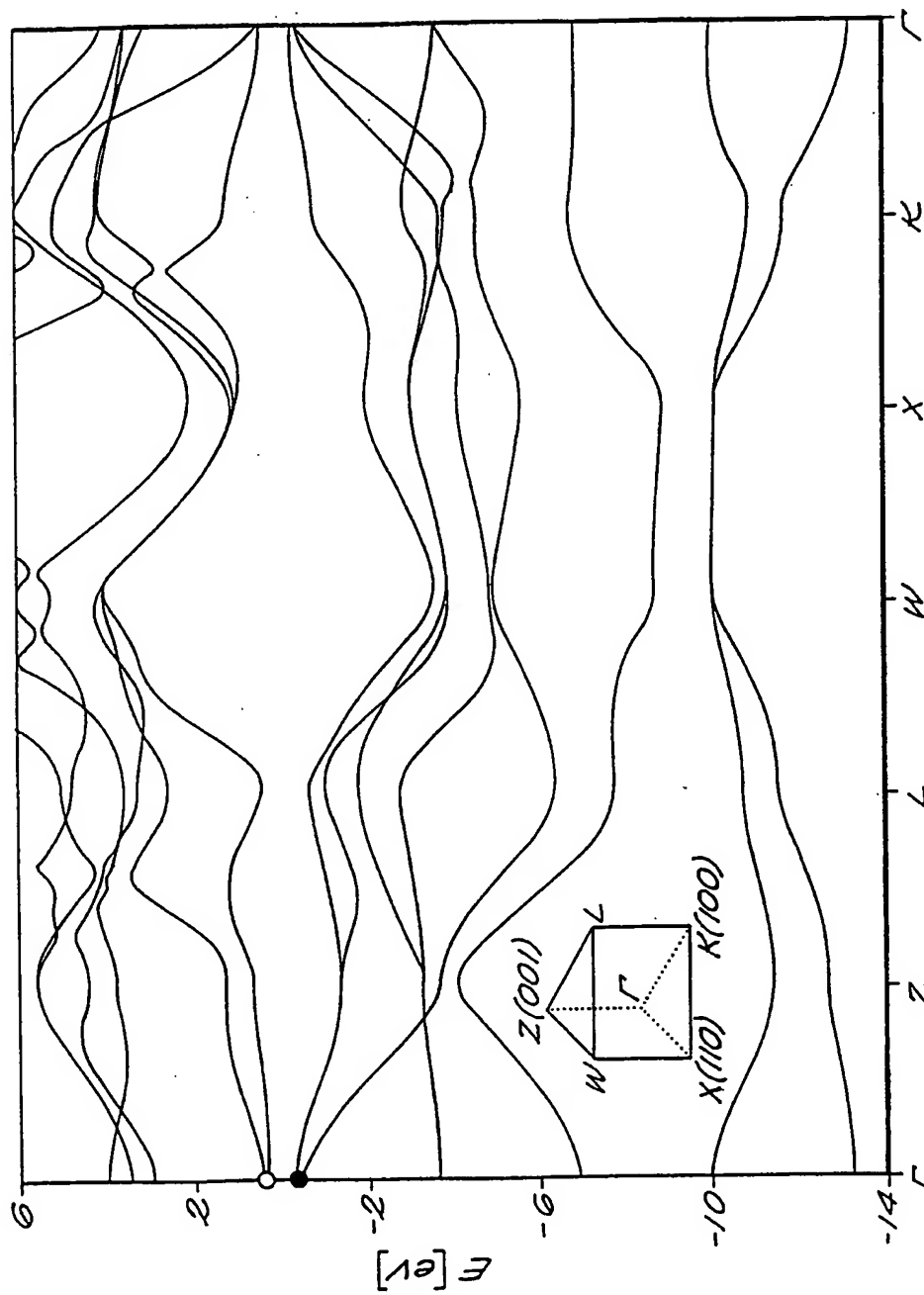
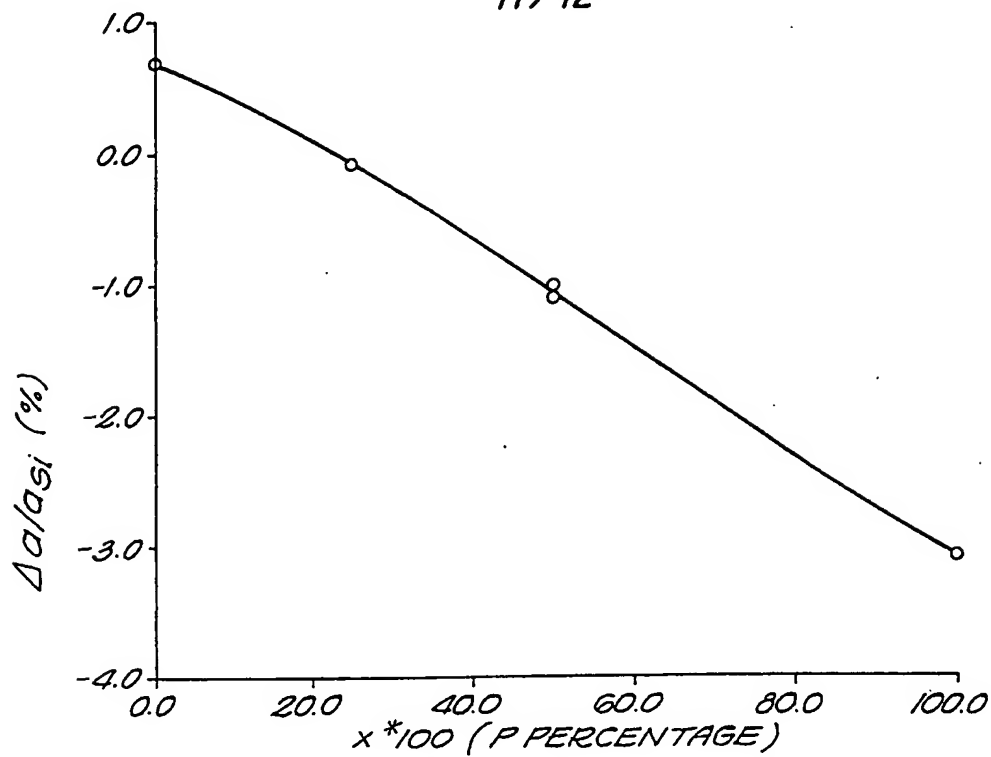
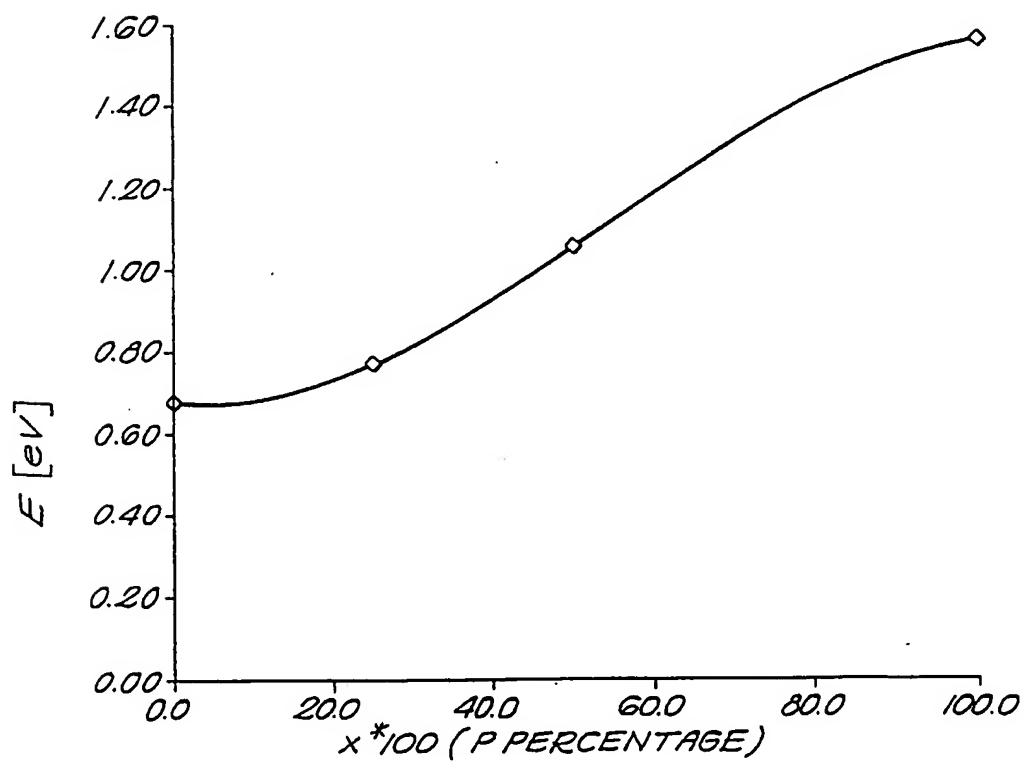


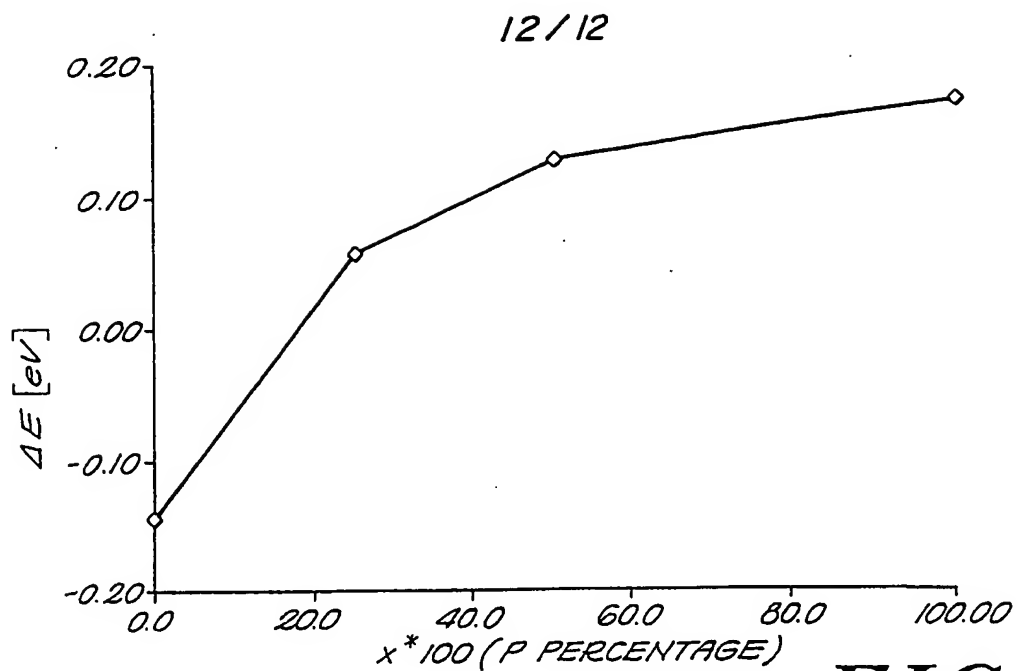
FIG. 9

10/12

**FIG. 10**

11/12

**FIG. 11****FIG. 12**

**FIG. 13****FIG. 14**